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Economics of Reverse Osmosis and Multistage Evaporation for Concentrating Skim Milk from 8.8 to 45% Solids

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ABSTRACT

Reverse osmosis used in the concentration range of 8.8 to 25% by weight of solids reduces the cost of concentrating skim milk in comparison of multistage evaporation. Membranes used for skim milk limit the maximum practical concentration to approximately 25%. When reverse osmosis and multistage evaporation are used in combination to concentrate skim milk from 8.8 to 45% solids, with a reverse osmosis final concentration of 25%, capital and operating costs are equivalent to those for multistage evaporation from 8.8 to 45%. However, energy requirements for the combination of reverse osmosis and evaporation are much lower than for multistage evaporation alone, a minimum of 75,800 kJ/Mg of water removed (reverse osmosis 8.8 to 25%; multistage evaporation 25 to 45%) versus 277,000 for evaporation. This study presents preliminary approximation of costs and economics for reverse osmosis and a preliminary economic comparison of reverse osmosis, evaporation, and the combination of reverse osmosis and evaporation. The concentration range of 8.8 to 45% solids is typical for feed preparation of skim milk before spray drying to powdered skim milk.

INTRODUCTION

This paper reports one phase of a study of low-energy processes for concentrating fluid foods undertaken jointly by the United States Department of Agriculture and the Department of Energy. Results of this economic comparison indicate potential savings of costs and energy for skim milk processors from the use of reverse osmosis in the concentration process. The potential for savings from the use of reverse osmosis by the dairy industry is amply documented (5). The reverse osmosis operation would be used to treat the skim milk, which is initially at 8.8% solids, at the lower concentration range. This is advantageous in comparison to evaporation, because reverse osmosis, which is lower in cost and uses less energy, would remove a greater quantity of water at the lower to intermediate concentrations (10). This arrangement also coincides with the current physical properties and limitations of available membranes and characteristics of the reverse osmosis process, which is that greater flux is achieved at lower concentrations for equal area and pressure (9). This paper is to present preliminary cost comparison between reverse osmosis, thermal evaporation, and the combination of reverse osmosis and evaporation. I believe that actual component costs of the total costs for each process are realistic and represent average costs for comparison. However, costs for labor, electricity, fuel, and raw materials vary with geographical location, and equipment costs vary with size and type. Therefore, each processor must calculate total costs for each particular situation. The main point is to indicate that processors of skim milk should investigate the use of reverse osmosis and evaporation in the combination that is most economical for them. Therefore, although this paper presents some of the cost details, it does not present an exhaustive discussion. Instead, we present a concise cost comparison. Anyone interested in the background or details of the cost estimate may request them from the Eastern Regional Research Center, Engineering Science Laboratory.

Concentration ranges of 8.8 to 13.9, 17.6, and 21.3% were used to divide the 8.8 to 25% range to determine the variation of cost with

concentration and to see if any range corresponding to minimum cost existed. Also, it is conceivable that a plant might want to operate near one of the intermediate ranges. The practical upper limit of 25% concentration was recommended by the manufacturer of the reverse osmosis membrane. Total costs for fixed capital investment are believed to be accurate to ±20%. Operating costs and selling prices should range about ±10%.

BASIS OF COST ESTIMATE

Cost estimates are based on processing 9,070 kg/h of skim milk at 8.8% solids by weight to 45% solids. This corresponds to a medium to large plant as determined from information supplied by equipment vendors and the literature (3). A larger plant was chosen because, in general, it would be more economical. The process operates 20 h per day, requiring approximately 3.5 h per day for clean-in-place system operation. The number of operating days per year is 331. Cost data correspond to the first quarter of 1981. Selling prices are based on 20% per year net return on fixed capital. Total costs include all costs but not net profit and income taxes.

No allowance was included in operating cost for product losses. This is because product loss is low for both processes, and, therefore, this factor would not affect the cost comparison. Also, the permeate concentration is low (ca. .1%), and, therefore, any sewer charges for reverse osmosis would be equivalent to sewer charges for evaporation where the effluent originates from vapor entrainment and washdown of equipment.

The requirement of fixed capital for the processes is the cost for a complete plant with all new equipment. However, it is likely that either reverse osmosis or evaporation units would be added to an existing plant. For addition to existing plants, the actual cash required for investment would be reduced to the extent that existing facilities are used. Nevertheless, the costs shown here for new facilities represent a conservative approximation of the cost for an addition to an existing plant, because existing facilities used for the new process cannot be used for some other process. In other words, for comparison, all processes should be charged for the equipment and facilities used and not be given free use of existing capital. Direct operating costs for reverse osmosis are calculated from vendor information for plate and frame type equipment. This paper considers only a plate and frame type unit because this was the only one studied. It was selected for the pilot plant because of the ease of studying various types of membranes, and also because this type is used in commercial plants and uncertainty in scaling up data would be unlikely.

Fixed capital costs are based on equipment vendor costs for the evaporator and reverse osmosis units. Total installed fixed capital cost is calculated by the factored estimate method (6). This method is accurate enough for approximating capital and operating costs and for comparing the two processes.

Evaporator costs are based on six-stage multiple-effect evaporation. Six-stage thermal evaporation was used because it is accepted currently in the dairy industry as the most economical thermal evaporation process for this capacity range, according to information from evaporator vendors. Evaporator area required varies from approximately 465 m^2 for concentrating from 13.9 to 45% to about 223 m^2 for concentrating from 25 to 45%. Steam requirement at the corresponding ranges varies from 454 to 170 kg/h. Requirements for an evaporator concentrating from 8.8 to 45% are 725 m^2 and 862 kg/h of steam. Evaporator area and steam requirements were calculated by a computer program written by Taylor (12) at the Eastern Regional Research Center by vendor information for heat transfer coefficients, flow pattern, and temperature of vapor in each stage. These calculations verified the vendor's stated steam economy of approximately .1 (kg steam required per kg water evaporated) and included factors of feed temperatures, condensate flows, heat recovery, and thermal vapor recompression — all of which affect the steam economy in addition to the number of physical evaporator effects. Cost for steam is $17.64/1,000 kg of steam. The latter will vary with process plant location, and a cost was selected to approximate the average. Reverse osmosis costs are based on a plate and frame type unit using approximately 18.6 m^2 per module. The area required for concentrating from 8.8 to 13.8% and 8.8 to 25% varies from 334 to 697 m^2 or 18 to 38 modules. The cor-
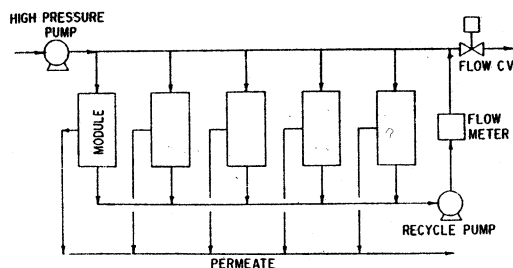
Figure 1. Typical reverse osmosis module flow schematic for a single stage.

relation of required area with flow was determined by Roger (8) at the Eastern Regional Research Center, and the optimum number of stages was calculated by a computer program written by Taylor (11) at the same location. These calculations and correlations were corroborated when a vendor independently proposed similar designs for the same concentration ranges and flow capacity. A typical reverse osmosis flow schematic for a single stage is in Figure 1. One high-pressure pump is required for up to six stages consisting of five or six modules.

COST RESULTS

Operating Costs

A comparison of operating costs per megagrams ($¢/Mg$) of water removed shows reverse osmosis is lower in cost than six-stage thermal evaporation, based on a 9.070 kg per h feed at 8.8% solids. Table 1 shows operating costs for reverse osmosis, six-stage thermal evaporation, and for combined processing by reverse osmosis followed by evaporation, respectively. Comparing sections A and B of Table 1, reverse osmosis shows a lower cost than evaporation per Mg of water removed. Over the same concentration range of 8.8 to 25.0%, reverse osmosis is 36% lower in cost than thermal evaporation. When reverse osmosis and multiple-effect evaporation are used in combination, the yearly costs are almost constant at about $550,000 per year, while the cost per megagrams of water removed is approximately 1,136¢.

Tables 2 and 3 show the direct operating costs for concentration ranges of 8.8 to 17.6% and 8.8 to 25% solids. Maintenance cost, which is not shown in the tables but is included in calculation of total operating cost, is esti-

TABLE 1. Operating costs (9,070 kg/h feed at 8.8% solids).

	Concentration (% solids)	($/yr)	($¢/Mg$ water removed)
A. Reverse osmosis (RO)	8.8−13.9	175,900	793.4
	8.8−17.6	233,900	779.9
	8.8−21.3	275,300	777.7
	8.8−25.0	302,200	777.5
B. Six-stage thermal evaporation (ME)	8.8−25.0	472,000	1,215.4
	8.8−45.0	545,000	1,128.3
	13.9−45.0	376,800	1,434.1
	17.6−45.0	316,600	1,731.6
	21.3−45.0	273,500	2,093.4
	25.0−45.0	239,800	2,553.0
C. RO and ME			
RO	8.8−13.9	552,700	1,144.4
ME	13.9−45.0	....	....
RO	8.8−17.6	550,500	1,139.8
ME	17.6−45.0	....	....
RO	8.8−21.3	548,800	1,136.2
ME	21.3−45.0	....	....
RO	8.8−25.0	542,000	1,122.1
ME	25.0−45.0	....	....

TABLE 2. Direct operating costs for reverse osmosis (RO) (9,070 kg/h feed, 8.8 to 17.6% concentration).

	Consumption	Cost per unit	Cost	Cost
			($/day)	(¢/Mg water removed)
1. Membranes	1.3 m²/day	107.0 $/m²	143.35	158.20
2. Cleaning agents				
a. RO compound	11.8 kg/day	3.26 $/kg	38.42	42.40
b. Citric acid	4.0 kg/day	1.65 $/kg	14.60	16.12
c. Hypochlorite	3.2 kg/day	1.43 $/kg	10.12	11.18
d. Total raw materials			63.14	69.70
3. Utilities				
a. Electricity	741.9 kWh/day	.035 $/kWh	25.97	28.64
b. Cooling water	34.30 m³/day	.154 $/m³	5.28	5.82
c. Steam	252 kg/day	17.64 $/Mg	4.45	4.92
d. Water (CIP)	9.76 m³/day	.198 $/m³	1.93	2.14
e. Total			37.63	41.52
4. Labor	2.5 man h/day	8 $/man h	30.00	33.11

mated at 3.0% per year of total fixed capital investment.

Capital Costs

Table 4, shows the capital costs for reverse osmosis, evaporation, and the combined processes. Capital cost for the combined processes is almost constant at about $2,600,000, whereas capital cost for equal water removal is greater for evaporation in the 8% to 25% range.

For six-stage thermal evaporation and for the combination of reverse osmosis and thermal evaporation, in sections B and C of Table 1, in the range of 8.8 to 45.0% concentration, costs are approximately equal. Therefore, the choice between alternatives in this concentration range will depend on relative operating costs for the particular plant location.

ENERGY REQUIREMENTS

Energy requirements for the processes are ir Tables 5 to 7. A comparison of energy re quirements for reverse osmosis and therma evaporation can be made from Tables 5 and (where the electrical and steam requirements respectively, are listed as kilojoules per mega gram water removed. From these two columns much more energy is required by evaporatio

TABLE 3. Direct operating costs for reverse osmosis (RO) (9.070 kg/h feed, 8.8 to 25.0% concentration).

	Consumption	Cost per unit	Cost	Cost
			($/day)	(¢/Mg water removed)
1. Membranes	1.3 m²/day	107.0 $/m²	143.35	172.01
2. Cleaning agents				
a. RO compound	15.4 kg/day	3.26 $/kg	50.14	42.69
b. Citric acid	11.5 kg/day	1.65 $/kg	19.06	16.23
c. Hypochlorite	9.2 kg/day	1.43 $/kg	13.21	11.25
d. Total raw materials			82.41	70.17
3. Utilities				
a. Electricity	875.9 kWh/day	.035 $/kWh	30.66	26.11
b. Cooling water	43.23 m³/day	.154 $/m³	6.66	5.67
c. Steam	329 kg/day	17.64 $/Mg	5.80	3.09
d. Water (CIP)	13.74 m³/day	.198 $/Mg	2.72	2.32
e. Total			43.67	37.19
4. Labor	2.5 man h/day	8 $/man h	30.00	25.56

TABLE 4. Capital investment (9,070 kg/h feed at 8.8% solids).

	Concentration	Fixed capital	Working capital	Total
			($)	
A. Reverse osmosis (RO)	8.8—13.9	866,400	18.700	835,000
	8.8—17.6	1,110,000	25,200	1,135,200
	8.8—21.3	1,314,000	30,000	1,344,000
	8.8—25.0	1,440,000	33,000	1,473,000
B. Six-stage thermal evaporation (ME)	8.8—25.0	2,129,000	43,000	2,172,000
	8.8—45.0	2,520,000	50,000	2,570,000
	13.9—45.0	1,775,000	36,000	1,811,000
	17.6—45.0	1,454,000	30,000	1,484,000
	21.3—45.0	1,213,000	26,000	1,239,000
	25.0—45.0	1,015,000	23,000	1,038,000
C. RO and ME				
RO	8.8—13.9	2,591,400	54,700	2,646,100
ME	13.9—45.0	....	....	....
RO	8.8—17.6	2,564,000	55,200	2,619,200
ME	17.6—45.0	....	....	....
RO	8.8—21.3	2,527,000	56,000	2,583,000
ME	21.3—45.0	....	....	....
RO	8.8—25.0	2,455,000	56,000	2,511,000
ME	25.0—45.0	....	....	....

for water removal — on the order of 9 to 10 times as much as for reverse osmosis in terms of directly applied energy (or, in other words, the form of energy used by the process). The relative energy ratio decreases, when the amount of the original source of energy supplied by fuel is compared, to 2.3 to 3.1 times as much energy required for evaporation. As shown in Table 7, increasing the proportion of water removed by reverse osmosis in the combined process greatly reduces the energy requirement. For instance, increasing the water removed by reverse osmosis by 75% reduced the energy requirement 54%, from 166,100 to 75,800 kJ/Mg water removed.

Similarly, the original fuel combustion required is reduced from 258,800 to 158,900 kJ/Mg water removed.

Energy conversion efficiencies for fuel to steam and for fuel to electrical energy were selected as average. Efficiencies, of course, will vary with plant size, energy sources, type of equipment, and operating temperatures and pressures. Local (in-plant) electricity generation may be less efficient than generation by utility company. For steam generation, .8 was used. For steam to mechanical energy, a thermal efficiency of .35 was used. This may range from .15 to .42. The turbine to generator efficiency

TABLE 5. Energy requirements for reverse osmosis (9,070 kg/h feed at 8.8% solids).

Product concentration	Electricity			Fuel
(% solids)	(kWh/day)	(kWh/Mg water removed)	(kJ/Mg water removed)	(kJ/Mg water removed)
13.9	674.9	10.077	36,300	152,400
17.6	741.9	8.187	29,500	123,800
21.3	808.9	7.563	27,200	114,500
25.0	875.9	7.460	26,900	112,800

TABLE 6. Energy requirements for six-stage evaporation. (9,070 lb/h feed at 8.8% solids)

Concentration	Steam		Fuel
(% solids feed — product)	(kg/kg water removed)	(kJ/Mg water removed)	(kJ/Mg water removed)
8.8—45.0	.1182	275,000	344,300
13.9—45.0	.1185	275,700	346,600
17.6—45.0	.1188	276,400	346,600
21.3—45.0	.1192	277,300	346,600
25.0—45.0	.1198	278,700	348,900

used was .85. The general range is .82 to .98. Multiplying the three efficiencies (.8 × .35 × .85) results in a overall fuel to electrical conversion of .238. Data and discussion of efficiencies are in (1, 2, 4).

ECONOMIC AND FINANCIAL SUMMARY

The cost and economic factors for the combined process are in Table 8. The table also shows individual factors for each process. A net return on fixed capital of 20% per year is used for this case. This return is probably low at today's extraordinary interest rates. A higher return probably would be necessary to provide the incentive for investment in new production facilities. However, the prospective investor may add his own required profit to the total

cost (item 3 in table) to calculate his selling price.

An article comparing costs of evaporation, reverse osmosis, and freeze concentration has been published (7). Bases of comparison in the authors' estimates differ from this estimate. Nevertheless, their ranges of costs for reverse osmosis appear reasonable and would approximately agree with this estimate after adjustments to a common basis and a specified type of reverse osmosis equipment.

If the concentrate could be sold for the prices in the economic summary table, the combined process appears to be economically feasible. The break-even point for the processes is about 21% of annual production. This reduces the risk of a financial loss due to lost production or lower market prices than planned

TABLE 7. Energy requirements for reverse osmosis and evaporation in sequence (9,070 kg/h feed at 8.8% solids).

Concentration			Total — electrical and steam —		Fuel
(% solids)	(kJ/Mg water removed)	(Mg water removed/yr)	(kJ/ yr × 10⁶)	(kJ/Mg water removed)	(kJ/Mg water removed)
RO (8.8—13.9)	36,290	22,168	804.5		152,400
ME (13.9—45.0)	275,700	26,272	7,242.5		346,600
		48,440	8,047.0	166,100	257,700
RO (8.8—17.6)	29,500	29,991	884.0		123,800
ME (17.6—45.0)	276,400	18,280	5,052.1		346,600
		48,271	5,936.1	123,100	208,200
RO (8.8—21.3)	27,200	35,401	964.4		114,500
ME (21.3—45.0)	277,300	13,065	3,623.1		346,600
		48,466	4,587.5	94,700	177,000
RO (8.8—25.0)	26,900	26,900	1,044.3		112,800
ME (25.0—45.0)	278,700	9,394	2,618.0		112,800
		48,263	3,662.3	75,800	158,900

TABLE 8. Financial and economic summary (9,070 kg/h feed at 8.8% solids); 20% net annual return on fixed investment.

	Reverse osmosis, 8.8–25%	Six-stage evaporation, 25–45%	Reverse osmosis and six-stage evaporation 8.8–45%
1. Fixed cost, $/yr	145,400	103,400	248,800
2. Variable costs, $/yr	183,200	155,000	338,200
3. Total costs (1 + 2), $/yr	328,600	258,400	587,000
4. Federal income tax, $/yr	245,400	172,900	418,300
5. Net profit, $/yr	288,000	203,000	491,000
6. Total sales (3 + 4 + 5), $/yr	862,000	634,300	1,496,300
7. Fixed capital, $	1,440,000	1,015,000	2,455,000
8. Working capital, $	33,000	23,000	56,000
9. Total capital (7 + 8), $	1,473,000	1,038,000	2,511,000
10. Depreciation, $/yr	72,000	1,038,000	122,800
11. Cash flow (5 + 10), $/yr	360,000	253,800	613,800
12. Capital recovery rate (11 ÷ 7),/yr	.25	.25	.25
13. Return on fixed investment (DCF, uniform earings), %	24.7	24.7	24.7
14. Project life, yr	20	20	20
15. Annual earnings on fixed capital, %	20	20	20
16. Annual earnings on total capital, %	19.6	19.6	19.6
17. Turnover ratio (6 ÷ 7)	.60	.62	.61
18. Net profit on sales (5 ÷ 6), %	33.4	32.0	32.8
19. Selling price, ¢/Mg water removed	2,217.6	6,752.6	3,098.0
20. Break-even point, Mg water removed	8,327	2,026.4	10,376.1
21. Yearly production, Mg water removed	38,870	9,394	48,299
22. Cost/kg of solids, ¢ (3 ÷ 5,283,990)	6.22	4.87	11.09
23. Selling price/kg of solids, ¢ (6 ÷ 5,283,990)	16.32	12.00	28.31

for the project. Those interested in obtaining more details about the capital and operating costs may request them from the author.

RECOMMENDATIONS

Economics of concentrating skim milk using reverse osmosis are advantageous in comparison to evaporation only. However, each processor should analyze the economics for his individual plant. This is required because the economics are dependent on the quantity of skim milk processed, concentration ranges, additional facilities and utilities required, and selling prices for the product. Also, operating costs, such as costs for fuel, electricity, labor, and raw materials vary with geographical location.

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